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Modeling Laser Damage Caused by Platinum Inclusions in Laser Glass

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Modeling Laser Damage Caused by Platinum Inclusions in Laser Glass*

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A fracture-mechanic theory suggests that crack-propagation rates are proportional to the square root of the inclusion radius and to the three-quarters power of the fluence. The theory does not yet account for pressure loss or convection heat transfer as platinum vapor flows into the crack, and needs to be developed further before accurate propagation rates can be predicted. However, a simple estimate obtained by multiplying the time that the platinum is in the vapor state by the sonic velocity in glass gives a conservative but reasonable result. At fluence levels of 2 J/cm^2, crack propagation of 4 µm per shot are predicted.

A crack-development hypothesis, based on shock-wave propagation, successfully predicts the shape of typical damage sites. The sites have an annular crack extending from the equator of the inclusion and planar crack lobes extending from the poles. The lobe at the pole exposed to laser light is larger than the lobe at the unexposed pole.

A numerical heat-transport model predicts temperature profiles in and around a metallic platinum inclusion imbedded in a phosphate laser glass matrix when illuminated with 1-µm laser light. The thermal model predicts that glass damage will occur if the platinum temperature exceeds the boiling point. Predicted fluence-damage limits of 1.4 J/cm^2 for a 1-ns pulse and 4.3 J/cm^2 for a 10-ns pulse agree with experimental data. The damage limit is independent of inclusion size above about 1 µm in diameter.

Key words: crack propagation rates; damage sites; glass fracture; fluence damage limits; Nova laser; platinum inclusions; thermal modeling.

1. Introduction

Platinum inclusions in neodymium-doped phosphate laser glass on Nova and Novette have been the cause of glass damage when fluence levels greater than about 2 J/cm^2 were reached. Laser light is absorbed by the opaque platinum, causing a thin skin of platinum on the front surface of the inclusion to vaporize. A shock wave propagates through the inclusion and is transmitted to the glass. Glass, being a brittle material, cracks because of the shock wave and the pressure of the vaporized platinum. These cracks propagate until the pressure of the vaporized platinum decreases below that required for further crack propagation.

The phenomena was studied as early as 1970 by Hopper and Uhlmann [1]. They showed photographs of damaged glass and calculated temperatures exceeding 10 000 K when fluence levels were 20 J/cm^2 over a 30-ns period. They theorized that very small inclusions were safe because heat losses to the glass kept the temperatures and, hence, stresses within allowable bounds. However, they argued that for sizes above 1000 Å (0.1 µm), the strength of the glass was exceeded and the glass could fracture. Their thermal modeling suggested that large inclusions were less damaging than intermediate-sized ones (over 1000 Å) because the surface-to-volume ratio of the inclusion decreased as the radius increased. Therefore, the larger inclusions had more thermal capacity and hence lower average temperatures and stresses.

Sparks and Duther [2] also examined the inclusion problem and showed that glass damage was greater with high-intensity, short-pulse lasers than with low-intensity, long-pulse lasers. A number of authors [3-5] have studied heating of a sphere illuminated from one side.

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Their solutions all show that the high temperatures predicted by Hopper and Uhlmann will exist.

We discuss three items in this paper:

- A fracture-mechanics theory suggesting that glass damage will be worse with larger inclusions;
- A hypothesis explaining the shape that typical cracks develop in the glass and that matches many damage sites; and
- Thermal modeling results suggest a fluence threshold of 1.4 J/cm^2 for a 1-ns pulse or 4.3 J/cm^2 for a 10-ns pulse in phosphate glass. This threshold is independent of inclusion size above about 1 μm in diameter. The thermal modeling results compare favorably with experimental data.

2. Fracture-Mechanics Theory

Consider glass to be a brittle material initially with a penny-shaped crack that is the diameter of the platinum inclusion. The criterion for crack propagation is based on a material property, K_1, called the fracture-toughness (stress-intensity) factor [6]

$$K_1 = \sigma \sqrt{\pi a} \qquad (1)$$

where

$K_1 \equiv$ material fracture toughness (Pa $\sqrt{m}$)

$\sigma \equiv$ applied stress (or pressure), Pa

$a \equiv$ crack radius (which we take initially equal to the inclusion radius), m.

If the value of K_1 exceeds a critical value, then the crack will propagate. This critical value termed the critical-fracture-toughness or critical-stress-intensity factor, K_{1C}, is a material property, the magnitude of which is normally obtained experimentally.

The Mie-Grüneisen equation of state [7,8] is applicable for shock-wave/high-stress values, where energy is deposited isochorically; it relates stress and specific energy as

$$\sigma = \Gamma \rho e \qquad (2)$$

where

$\Gamma \equiv$ Grüneisen constant (dimensionless)

$\rho \equiv$ density (Kg/m^3)

$e \equiv$ specific energy deposition above that required for vaporization (J/Kg).

Following Hopper and Uhlmann's article [1] for an inclusion with finite thermal diffusivity and a 10-J/cm^2, 1-ns pulse, we have a spatial temperature distribution using their material properties (see their Eqs. (6) and (7b)).

$$T_{\substack{1\ \mathrm{ns} \\ 10\ \mathrm{J/cm^2}}} \approx 4 \times 10^4 \cdot \left(\frac{1\ \mathrm{ns}}{30\ \mathrm{ns}}\right)^{1/2} \cdot \left(\frac{10\ \mathrm{J/cm^2}}{0.7\ \mathrm{J/cm^2}}\right)$$

$$\cdot\ \mathrm{ierfc}\left(\frac{0.6\ z}{(1\ \mathrm{ns}/30\ \mathrm{ns})^{1/2}}\right)$$

$$\approx 1 \times 10^5\ \mathrm{ierfc}\ (3.286\ z) \quad . \tag{3}$$

Here z is the distance into the inclusion from the surface in µm, and T is temperature in K. Values of ierfc, the integral of the complementary error function, are tabulated by Abramovitch and Stegun [9]. The surface temperature drops below the vaporization temperature (4800 K) at z = 0.307 µm. If we double the fluence to 20 J/cm^2, the temperature drops below the vaporization temperature at z = 0.371 µm. If we use these values to calculate the power dependence of the fluence, J, on the specific energy deposition (recalling that specific energy deposition is approximately proportional to temperature)

$$\left(\frac{J}{J_0}\right)^m = \frac{\rho e}{\rho e_0} \approx \frac{T}{T_0} \tag{4}$$

$$\left(\frac{20\ \mathrm{J/cm^2}}{10\ \mathrm{J/cm^2}}\right)^m = \frac{20\ \mathrm{J/cm^2}/0.371\ \mu\mathrm{m}}{10\ \mathrm{J/cm^2}/0.307\ \mu\mathrm{m}}$$

$$m = 3/4 \quad .$$

Combining this result with equations (1) and (2) we have

$$K_1 \sim J^{3/4} a^{1/2} \ . \tag{5}$$

The crack will propagate as long as $K_1 > K_{1C}$. Hence, this model suggests that the extent of crack propagation in the glass per shot is proportional to the square root of the crack radius and the three-quarters power of the fluence. Initially, the crack radius is equal to that of the inclusion but it would increase after each shot. Hence, at constant fluence, the rate of crack propagation would increase after each shot.

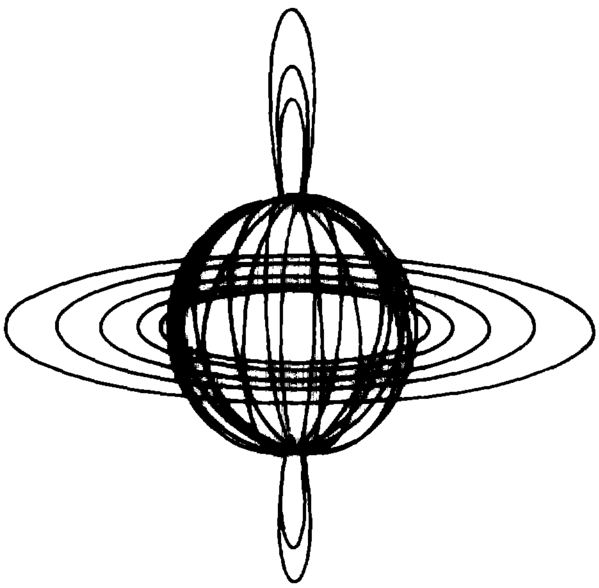
The model does not account for loss of pressure or convection heat transfer as the vaporized platinum flows into the crack, both of which counteract the effect of increasing crack propagation rate in later shots by making it harder to propagate a large crack. Both effects oppose the square root dependence of the crack radius, and could partially account for some experimental data [10,11,12,13], where the amount of crack propagation first increases and then decreases; or alternately propagates and then stops. Another reason cracks could stop propagating in later shots is that all the platinum initially in the inclusion has been deposited in the crack area with a thickness that is now transparent to laser light. Regardless, this model suggests that the larger the inclusion, the worse the damage.

Additional development of this fracture-mechanics theory could lead to a better prediction of how far a crack would propagate during a particular shot. In order to proceed further, we may need to estimate the thickness (width) of a typical crack so that we can calculate the pressure distribution in the crack as a function of time. Further, we may need to account for the change in opacity below unity of platinum deposited in the crack region if the platinum thickness is in the 100-Å, or less, range.

3. Crack-Development Hypothesis

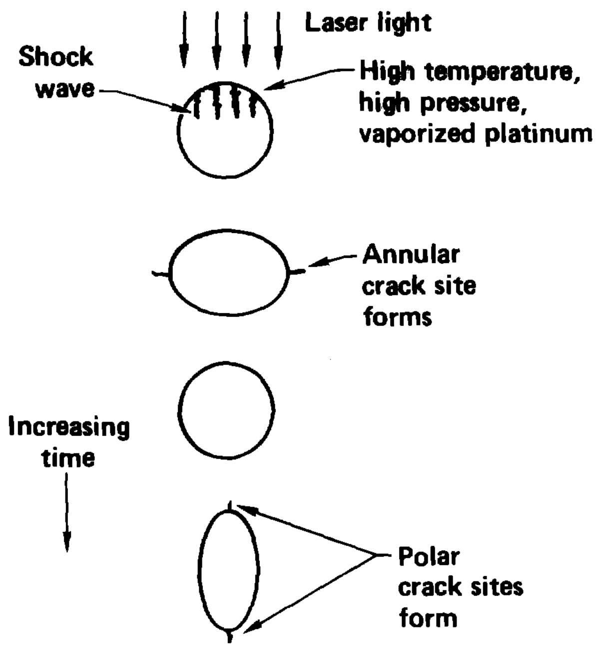
Many damage sites have an annular crack around the equator of the inclusion with an additional planar lobe-shaped crack at each pole [13,14] (see Fig. 1a). The crack at the pole, facing the laser light illumination, is always larger than the crack at the pole hidden from the laser light illumination by the inclusion itself.

During discussions with Hovingh [15], he suggested the phenomena was a result of shock propagation. As energy from laser light is deposited on the surface of the inclusion, a shock wave is developed that propagates through the inclusion (see Fig. 1b), which deforms to an oval shape, putting pressure at the sides of the inclusion. This initiates an annular crack site at the equator. The pressure over the annulus is uniform because of symmetry and a completely symmetric annular crack site is formed.



Typical geometry of many fracture sites

Figure 1a



Deflection of an inclusion with time

Figure 1b

Figure 1. Sketch of a typical damage site and a shock propagation analogy of why this geometry occurs.

It has been asked how pressure can cause a crack site because the pressure forces are compressive. The pressure is applied not only perpendicular to the incoming laser light, but also parallel to it, thereby tending to spread the glass material in tension parallel to the incoming laser light. A similar phenomenon occurs in the walls of a spherical pressure vessel, where the hoop stess is tension and yet there is pressure exerted on the inside wall surface. Further, any compression generated at the crack site changes to tension as the shock passes through the glass material itself.

The shock continues through the inclusion, dissipating energy and becoming weaker with time. The inclusion returns to a circular shape, but then deforms to an oval shape with a major axis parallel (rather than perpendicular) to the direction of the incoming laser light. However, the oval formed has a much more concentrated deformation at the poles because of the concentration of energy deposition there. Crack sites are initiated at the poles only and not as a complete annulus.

An analogy to this type of deformation occurs when a golfer hits a good drive. The golf ball has energy deposited at the surface, deforms to an oval with major axis perpendicular to the direction of the golfer's swing. During flight, the golf ball returns to circular shape and then deforms to an oval with the major axis parallel to the direction of the golfer's swing.

This crack-development hypothesis explains why the form of many crack sites are as shown in Figure 1a. The hypothesis suggests the location of crack initiation sites. However, it is the vaporized platinum and its associated pressure that actually propagate the cracks beyond the initial site. Because the platinum vapor must flow further to reach the crack site at the pole hidden from the laser light, pressure developed there is less than at the opposite pole crack site. Hence, a smaller crack should develop at the hidden pole than at the exposed pole. This is verified in observed glass damage sites.

4. Thermal Modeling

Our thermal model was a half-sphere of platinum surrounded by a half-spherical annulus of glass as shown in Figure 2a. The model represents what could be a typical inclusion, shown in Figure 2b. Vaporization of the platinum is concentrated at the top of the inclusion, which in both cases is normal to the incident laser light. Hence, the spherical model is a good approximation to the more generally shaped inclusion of Figure 2b. We use just a half-sphere in the model because of symmetry. In the model, laser light was absorbed on the upper surface of the platinum sphere with a cosine distribution used to account for the curvature of the surface.

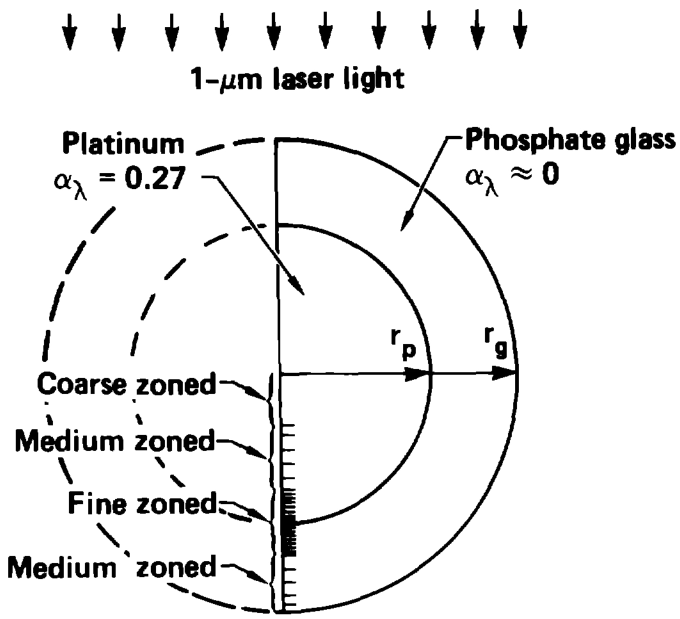


Figure 2a

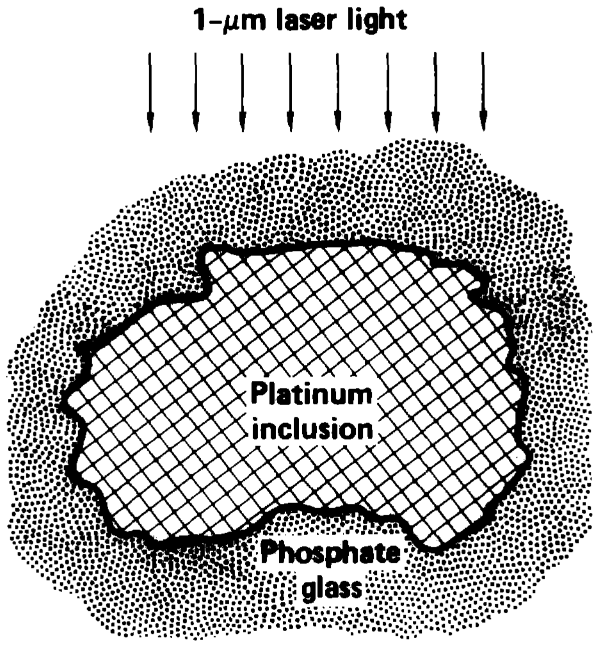


Figure 2b

Figure 2. Hemispherical model of a platinum inclusion in glass illuminated from the top with laser light, and what could be a typical non-spherical inclusion

Thermal properties used in the model for platinum and glass are shown in table 1. Platinum properties were obtained from Touloukian, et. al., [16] and Hampel [17]. The boiling point shown in Table 1 is higher than in some other references (e.g., Weast [18] shows 4100 K) but is used for consistency with other properties taken from Hampel [17]. The key platinum properties are the heat of vaporization and the normal spectral absorptance, so that the difference in the documented boiling point has an insignificant effect. The normal spectral absorptance shown is at room temperature. The absorptance does change with temperature, but it is more a function of the surface itself. Changes of an order of magnitude are feasible depending on whether the

Table 1. Thermal Properties of Materials Used in the Analysis

	Platinum inclusion	LHG-8 phosphate glass
Density, kg/m^3	21,400	2,850
Specific heat, J/kg K	146	263
Thermal conductivity, W/m K	80	0.52
Melting point, K	2,040	---
Heat of fusion, J/kg	101,000	---
Boiling point, K	4,800	---
Heat of vaporization, J/kg	2,260,000	---
Normal spectral absorptance at 1 μm	0.27	---

surface is polished or not and if the surface is oxidized. We used the room temperature value because no elevated temperature values were available. The equation of state for platinum above the boiling point was that used in the LASNEX Code [19]. Properties of glass were obtained from Stokowski, Saroyan, and Weber [20] for LHG-8 phosphate glass. The surface of the platinum was allowed to radiate to a 300-K surrounding. No absorption was permitted in the glass, but heat was conducted between the glass and the platinum with negligible contact resistance.

Modeling was performed using Shapiro's TOPAZ [21] code with Halquist's MAZE [22] and ORION [23] codes used for preparing the input and processing the output. TOPAZ is a heat conduction code, which is applicable to this problem because inclusion sizes are so small that natural convection is negligible. Problems were run on the CRAY computer with an average run time of about 30 minutes each.

Results are shown in Figure 3 where the fluence damage threshold is plotted against laser pulse length. Comparison with experimental data is excellent. Avizonis and Farrington [24] and Yamanaka [25] included error bars, which are also shown. The theory developed in this paper is the solid line, which has a slope of 1/2 corresponding to a square root dependence on laser pulse length. The slight departure of the theory from the data of Gonzales and Milam [26] at short laser pulse lengths may result from the crack propagation per shot being so small in this region. Hence, it takes a number of shots before any damage can be physically observed.

Temperature profiles at two different times are shown in Figure 4. Peak temperatures are high (electron volt range; 1 ev $\approx$ 10 000 K) and so are the resulting pressures of the vaporized platinum. Note that the temperature contours are all concentrated in the platinum at the exposed surface. There is no change in the temperature profiles when the size of the inclusion is changed above about 1 μm because the thin layer where the profiles are located is similar to a planar surface. Hence, results are independent of inclusion size above about 1 μm in diameter. Table 2 lists maximum temperatures, maximum pressures, and the resulting crack propagation per shot for various fluences. The maximum pressures were calculated using eq. (2). We used a Grüneisen constant, Γ, equal to unity; and a value of ρe calculated from the TOPAZ results at the time of the peak temperature by dividing the total energy in the vaporized platinum at the exposed pole by the volume of the vaporized platinum.

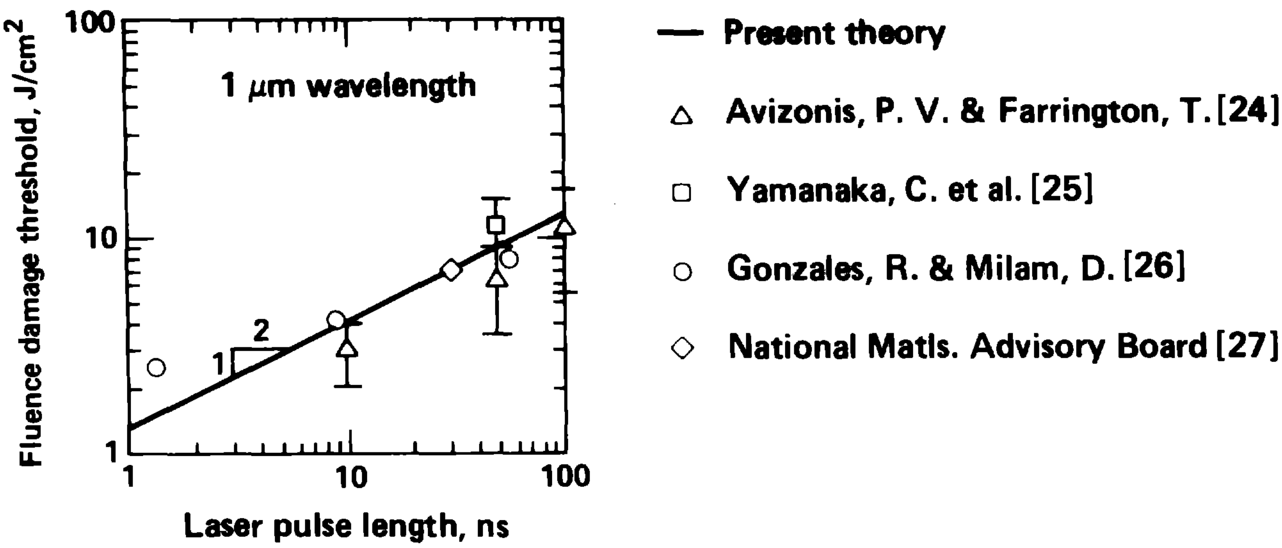
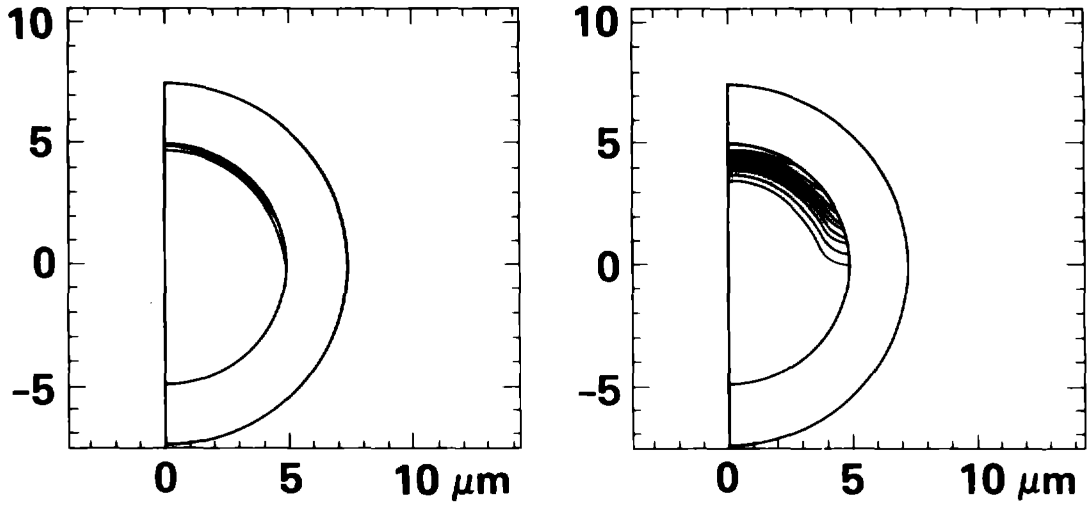


Figure 3. Effect of laser pulse length on the fluence damage threshold. Theoretical results are independent of inclusion size above about 1 μm in diameter and are in excellent agreement with experimental data.



Time, ns	1.0	10.0
Minimum contour, K	1500	570
Maximum contour, K	11000	2700

Fluence damage threshold is independent of inclusion size above 1 μm diameter

Figure 4. Temperature contours for a 5-μm-radius platinum inclusion surrounded by phosphate glass, and illuminated by 1-μm laser light at an incident fluence of 3.7 J/cm^2.

Table 2. Calculated Characteristics of Crack Propagation

Incident Fluence (J/cm^2)	Absorbed Fluence (J/cm^2)	Pulse Time (ns)	Maximum Temperature (K)	Maximum Pressure (Pa)	Crack Propagation Per Shot (μm)
37	10	1	1.3×10^5	2.8×10^{11}	500
18	5	1	7.6×10^4	1.5×10^{11}	150
3.7	1	1	1.5×10^4	0.5×10^{11}	8.4
1.8	0.5	1	6.5×10^3	$<0.5 \times 10^{11}$	3.5
1.5	0.4	1	5.3×10^3	$<0.5 \times 10^{11}$	1.5
3.7	1	10	4.5×10^3	-----	----

Fluence damage threshold is 1.4 J/cm^2 for a 1-ns laser pulse length

We have no doubt that the pressures are high enough to propagate a crack. In conjunction with experimental results [10-14], this suggests that damage will occur if the temperature of the platinum exceeds its boiling point . Experimental data (see Fig. 3) suggests a damage limit of about 2 J/cm^2 for a 1-ns pulse and 5 J/cm^2 for a 10-ns pulse. This is in agreement with the calculated values.

The fracture-mechanics theory is not developed enough to predict crack growth. However, crack growth can be conservatively estimated by multiplying the time during which platinum is in a vaporized state by the sound speed in glass. Values of crack growth for fluences close to those of available experiments are reasonable (see Table 2).

The key conclusion of this thermal analysis is that damage will occur if the platinum temperature exceeds the boiling point. Damage is independent of inclusion size (above about 1 μm) and is worse for shorter-duration laser pulses.

5. Conclusions

- Fracture-mechanics theory suggests that crack propagation rates are proportional to the square root of the inclusion radius and the 3/4 power of the fluence. Larger inclusions above about 1 μm in diameter are worse than smaller inclusions.

- A crack-development hypothesis based on shock propagation successfully predicts the shape of many fracture sites. The shape is that of an annular crack around the inclusion equator with planar lobes at the poles. The lobe at the pole exposed to laser light is larger than the lobe at the unexposed pole.

- Thermal modeling predicts that glass damage will occur if the platinum vaporizes and that the fluence damage threshold is both proportional to the square root of the laser pulse length and independent of the inclusion size above about 1 μm in diameter. Predicted fluence damage limits of 1.4 J/cm^2 for a 1-ns pulse and 4.3 J/cm^2 for a 10-ns pulse agree with experimental data.

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